# Indexing: Part I

CPS 216

Advanced Database Systems

## Announcements (February 3)



- Reading assignment for this week
  - R-tree (due Wednesday night)
  - GiST (due next Monday night, but try to read it by Thursday's lecture)
- Homework #1 due today (midnight)
- Homework #2 will be assigned next Thursday
  - Meanwhile, use the time to think about course project!
- No student presentation before midterm (so we can catch up with lectures)

## Basics



- Given a value, locate the record(s) with this value

```
SELECT * FROM R WHERE A = value;
SELECT * FROM R, S WHERE R.A = S.B;
```

- Other search criteria, e.g.
  - Range search

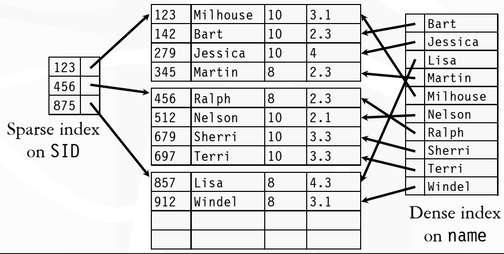
```
SELECT * FROM R WHERE A > value;
```

  - Keyword search

database indexing | Search

# Dense and sparse indexes

- Dense: one index entry for each search key value
- Sparse: one index entry for each block
  - Records must be clustered according to the search key






# Dense versus sparse indexes

- Index size
- Requirement on records
- Lookup
- Update



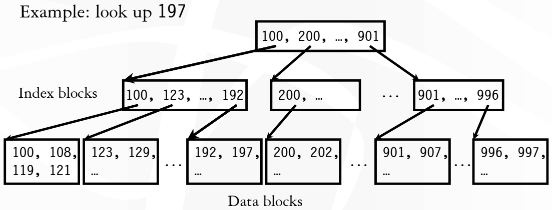
# Primary and secondary indexes

- Primary index
  - Created for the primary key of a table
  - Records are usually clustered according to the primary key
  - Can be sparse
- Secondary index
  - Usually dense
- SQL
  - `PRIMARY KEY` declaration automatically creates a primary index, `UNIQUE` key automatically creates a secondary index
  - Secondary index can be created on non-key attribute(s)
    `CREATE INDEX StudentGPAIndex ON Student(GPA);`

# ISAM

- What if an index is still too big?
  - Put a another (sparse) index on top of that!
  - ☞ISAM (Index Sequential Access Method), more or less

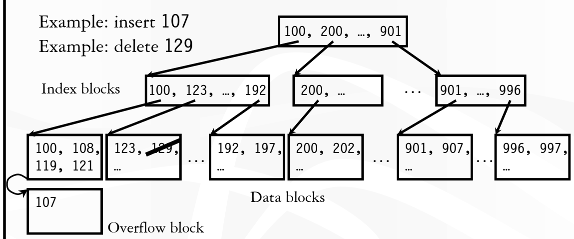
Example: look up 197






# Updates with ISAM

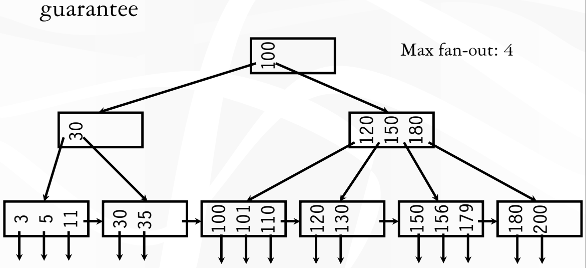
Example: insert 107
Example: delete 129



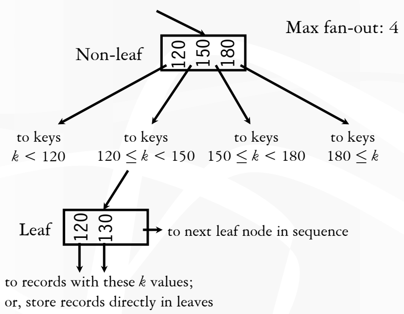



# B$^+$-tree

- Disk-based: one node per block; large fan-out
- Balanced (more or less): good performance guarantee



# Sample B$^+$-tree nodes






# B$^+$-tree balancing properties

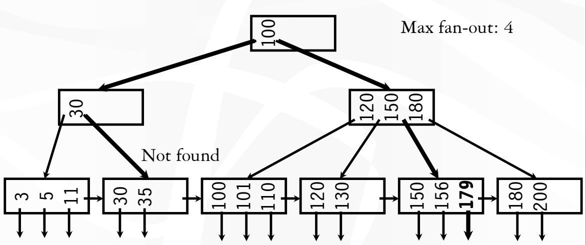
- All leaves at the same lowest level
- All nodes at least half full (except root)

| | Max # pointers | Max # keys | Min # active pointers | Min # keys |
|---|---|---|---|---|
| Non-leaf | $f$ | $f - 1$ | $\lceil f/2 \rceil$ | $\lceil f/2 \rceil - 1$ |
| Root | $f$ | $f - 1$ | 2 | 1 |
| Leaf | $f$ | $f - 1$ | $\lfloor f/2 \rfloor$ | $\lfloor f/2 \rfloor$ |



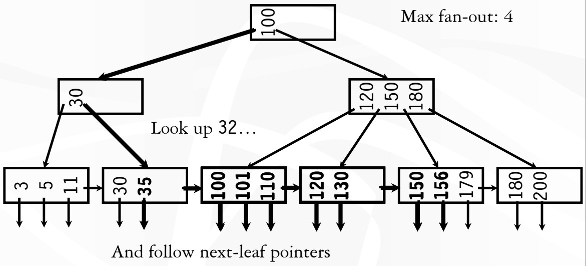
# Lookups

```
SELECT * FROM R WHERE k = 179;
SELECT * FROM R WHERE k = 32;
```



## Range query

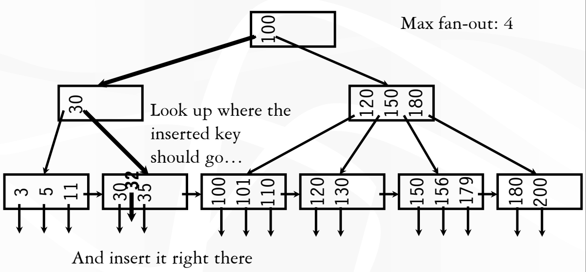
`SELECT * FROM R WHERE k > 32 AND k < 179;`






## Insertion

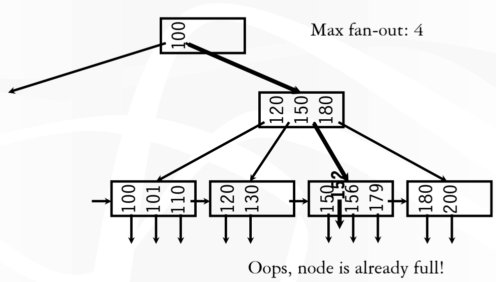
❖ Insert a record with search key value 32



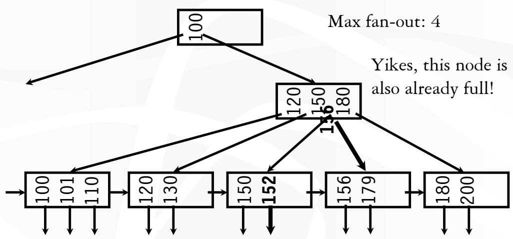



## Another insertion example

❖ Insert a record with search key value 152

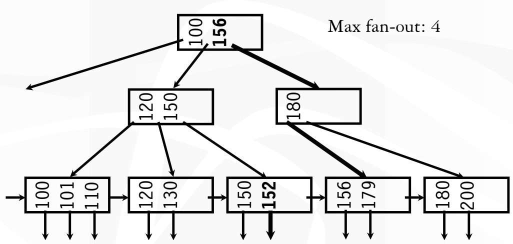


# Node splitting






# More node splitting

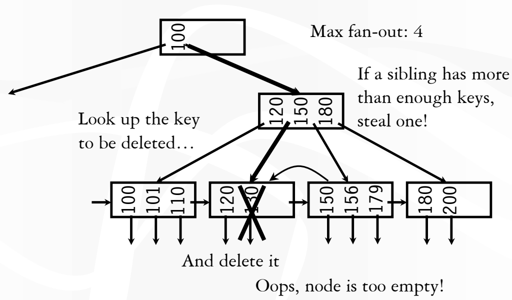



- In the worst case, node splitting can "propagate" all the way up to the root of the tree (not illustrated here)
  - Splitting the root causes the tree to grow "up" by one level

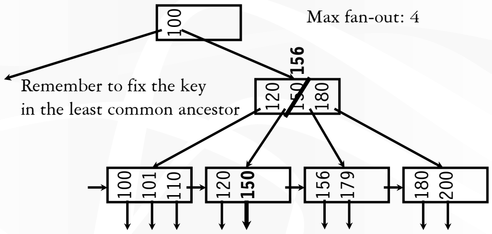


# Deletion

- Delete a record with search key value 130



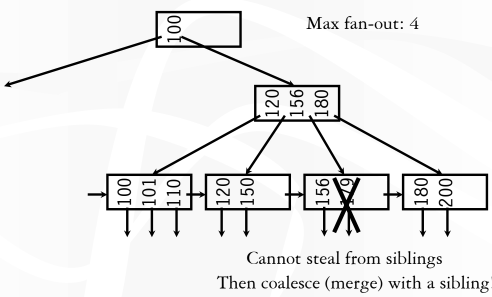
# Stealing from a sibling





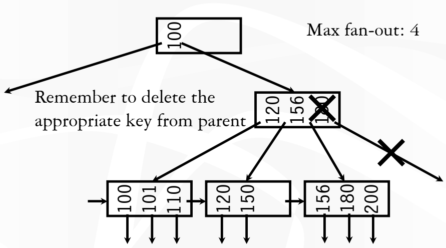

# Another deletion example

❖ Delete a record with search key value 179






# Coalescing




- Deletion can "propagate" all the way up to the root of the tree (not illustrated here)
  - When the root becomes empty, the tree "shrinks" by one level

## Performance analysis

- How many I/O's are required for each operation?
  - $h$ (more or less), where $h$ is the height of the tree
  - Plus one or two to manipulate actual records
  - Plus $O(h)$ for reorganization (should be very rare if $f$ is large)
  - Minus one if we cache the root in memory
- How big is $h$?
  - Roughly $\log_{\text{fan-out}} N$, where $N$ is the number of records
  - $B^+$-tree properties guarantee that fan-out is least $f / 2$ for all non-root nodes
  - Fan-out is typically large (in hundreds)—many keys and pointers can fit into one block
  - A 4-level $B^+$-tree is enough for typical tables



## $B^+$-tree in practice

- Complex reorganization for deletion often is not implemented (e.g., Oracle, Informix)
- Most commercial DBMS use $B^+$-tree instead of hashing-based indexes because $B^+$-tree handles range queries



## The Halloween Problem

- Story from the early days of System R…

```
UPDATE Payroll
SET salary = salary * 1.1
WHERE salary >= 100000;
```

  - There is a $B^+$-tree index on *Payroll*(*salary*)
  - The update never stopped (why?)
- Solutions?

## Building a $B^+$-tree from scratch

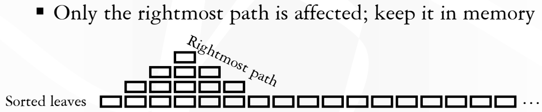


- ❖ Naïve approach
  - Start with an empty $B^+$-tree
  - Process each record as a $B^+$-tree insertion
- ❖ Problem

## Bulk-loading a $B^+$-tree



- ❖ Sort all records (or record pointers) by search key
  - Just a few passes (assuming a big enough memory)
  - More sequential I/O's
  - ☞Now we already have all leaf nodes!
- ❖ Insert each leaf node in order
  - No need to look for the proper place to insert
  - Only the rightmost path is affected; keep it in memory




## Other $B^+$-tree tricks



- ❖ Compressing keys
  - Head compression: factor out common key prefix and store it only once within an index node
  - Tail compression: choose the shortest possible key value during a split
  - In general, any order-preserving key compression
  - ☞Why does key compression help?
- ❖ Improving binary search within an index node
  - Cache-aware organization
  - Micro-indexing
- ❖ Using $B^+$-tree to solve the phantom problem (later)

## $B^+$-tree versus ISAM

- ISAM is more static; $B^+$-tree is more dynamic
- ISAM is more compact (at least initially)
  - Fewer levels and I/O's than $B^+$-tree
- Overtime, ISAM may not be balanced
  - Cannot provide guaranteed performance as $B^+$-tree does



## $B^+$-tree versus B-tree

- B-tree: why not store records (or record pointers) in non-leaf nodes?
  - These records can be accessed with fewer I/O's
- Problems?



## Coming up next

- Other tree-based indexs: R-trees and variants, GiST
- Hashing-based indexes: extensible hashing, linear hashing, etc.
- Text indexes: inverted-list index, suffix arrays